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Technical and economical evaluation of enhanced biomass to liquid fuel processes

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ABSTRACT

'Enhanced Biomass-to-Liquid' (EBtL) refers to BtL processes (biomass gasification and liquid fuel synthesis) with a significant increase in fuel production by means of external energy inputs. The conversion yield of biomass carbon into fuel carbon is multiplied by a factor of 3 in comparison with existing (autothermal) gasification processes. The technical options of such processes are outlined and evaluated in the paper: the production cost is estimated between 0.7 and 1.2 €/litre diesel.

EBtL routes enable a strong increase in biofuel production compared with today biofuel processes (i.e. ethanol plus vegetal oil). They may also be seen as an efficient way to store electricity and hydrogen (produced from processes generating no greenhouse gas emissions) into a liquid fuel made from renewable carbon and compatible with present motor technologies and fuel storage and distribution. In combination with hybrid motors (liquid fuel and electricity), these technologies may offer a realistic alternative to petroleum and help reducing greenhouse gas emissions.

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1. Introduction

The replacement of fossil fuels is a major challenge for the future, especially liquid fuels for road and air transport. The French consumption of liquid fossil fuels for transport was about 50 Mtoe in 2005 [1].

Hydrogen routes have the potential to replace petroleum [2], but they are still far from maturity: many problems are encountered in the fields of hydrogen production, storage and distribution, as well as engine developments.

Today, first generation liquid biofuels (i.e. ethanol and vegetal oil) have only a low potential: for a country like France, between 3 and 5 Mtoe/a seem feasible (10% of oil consumption for transport). But second generation BtL technologies highly improve this potential as the entire plant is transformed.

We define mass yield as the equivalent mass (on an energy equivalence basis) of diesel fuel produced for one mass unit of dry biomass put into a BtL process (NB: The lower heating value of BtL products is close to 45 MJ/kg, while the lower heating value of the diesel fuel, taken as a reference, is close to 42 MJ/kg; this affects the mass yield). The mass yield of existing BtL technologies is about 15–20% [3]. This is comparable to what is anticipated for future technologies of lignocellulose enzymatic transformation into ethanol [1]. This mass yield still leads to limited replacement of petroleum fuels by biomass fuels (about 7–10% in France). The aim of this paper is to show that the mass yield of BtL technologies can be increased by up to a factor of 3 (basically via external energy input) and that the resulting production costs can compete with gas-to-liquid (GtL) or coal-to-liquid (CtL) production costs, provided that environmental impacts are taken into account (e.g. via carbon tax). (GtL and CtL costs are about 0.3 $/l diesel [4].)

The paper summarizes the work done on the subject at CEA since 2001 [1,5–7]. Similar conclusions on potential fuel production enhancement have also been met meanwhile by other authors [4,8,9].

We start by explaining the origin of mass yield limitation for existing gasification and BtL processes. This will be done quantitatively, considering an entrained flow reactor technology. Various alternatives to increase the fuel production yield will then be discussed and the production costs will be assessed. Finally, overall benefits of these processes will be examined.

2. Biomass conversion technologies and related limitations today

Today, ethanol and vegetal oil production converts only a small fraction of the biomass input into fuel. Ongoing research on enzymatic conversion aims at enhancing the production of ethanol and other products (fatty acids, isoprenoids [10]), but the resource would remain only partially converted [1,8]. Biomass gasification has the potential to convert the whole resource into syngas for fuel synthesis.

The thermo-chemical process can be split into following main steps: biomass preparation, pyrolysis, gasification, gas cooling and

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cleaning, gas shift (in order to adjust the H_2/CO ratio) and fuel synthesis. Many different technologies exist for pyrolysis, gasification and gas cleaning [11–16], but some difficulties remain from an industrial point of view. Entrained-flow (EF) gasification has been identified as one of the most promising technologies for large-scale conversion of a variety of biomass streams into liquid transportation fuels [3,17–19]. The major advantages related to EF gasification are large-scale capacities, pressurisation, superior gas quality (maximization of CO and H_2 production due to high temperature and no tar forming) and compatibility with various resources. Furthermore, this technology is currently available for industrial coal gasification [19]. However, application of EF gasification to biomass is not straightforward and requires R&D, especially regarding biomass pre-treatment and feeding. Some experience with biomass EF gasifiers exists, for example the pilot scale gasifier of Future Energy [19] and the CHOREN gasifier [13]. This kind of gasification technology will be considered below.

The existing processes meet with their limitations in fuel production yield at three main stages:

1. in the gasification reactor: carbon and hydrogen are partially lost (i.e. oxidized) to provide energy for the endothermic gasification reactions,
2. during the water gas shift reaction: part of the CO is transformed into H_2 to adjust the H_2/CO ratio for the fuel synthesis reaction,
3. in the tail gases of the fuel synthesis stage: tail gases linked to Fischer–Tropsch synthesis represent typically 30 to 40 w% of the synthesis gas.

These limitations lead to a diesel mass yield of ~15% (i.e. ~150 kg diesel fuel for 1 ton dry biomass) and to an energy yield of ~30% for the produced fuel alone (the total energy yield for the unit is higher than 30% since part of the heat and of the lost carbon can be used to produce electricity: this production covers the needs of the production unit plus some excess electricity production). The total loss of carbon in this process is about 75% (~60% due to the chemical reaction path and ~15% due to various losses). Typically, only ~25% of the biomass carbon is converted into fuel carbon.

3. Increase of fuel production yield and related process alternatives

We propose that the fuel mass yield of the process can be multiplied by a factor 3 by implementing alternative technical solutions for the three limiting stages discussed above.

Physics impose that an increase of fuel production yield requires an additional energy input. One of the interest of thermo-chemical processes is that various primary energies are suitable, which allows for adaptation to local technical and economical specificities. Furthermore, EBtL routes may be considered as an efficient way to store electricity and hydrogen (produced from processes generating no greenhouse gas emissions) into a liquid fuel made from renewable carbon and compatible with present motor technologies and fuel storage and distribution.

The different process features and alternatives that we will assess are described below and summarized in Fig. 1.

3.1. Biomass preparation

Three preparation techniques are considered:

- slow pyrolysis (CHOREN NTV, producing a gas and solid char powder),
- fast pyrolysis (producing a slurry),
- torrefaction and milling (producing a solid powder).

3.2. Gasification

Gasification takes place in an entrained flow reactor at high temperature (~1500 °C). Ashes melt and are collected on reactor walls. Four alternatives for energy input are considered:

- autothermal reactor: energy is provided by partial oxygen combustion of the biomass with oxygen enriched air,
- allothermal reactor: energy is provided by three alternative technologies:

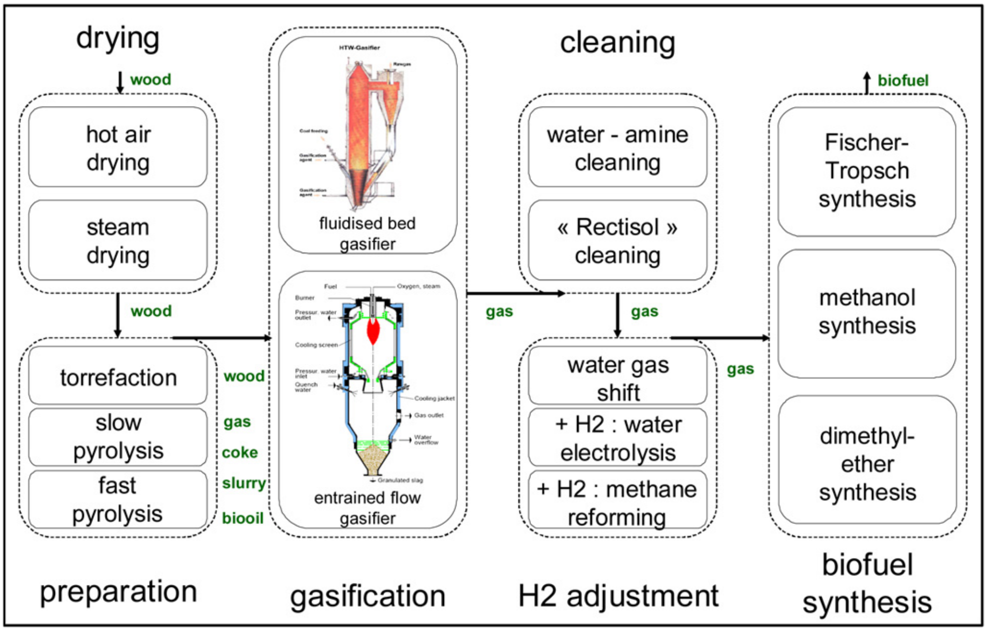

Fig. 1. Summary of process alternatives.

- plasma heating (i.e. electricity heating e.g. from nuclear power plants, wind mills),
- co-combustion of hydrogen,
- co-combustion of natural gas.

Plasma heating is a technology that does not exist at the industrial scale for gasification. Several authors have proposed implementing plasma technologies, mainly for inorganic and organic waste gasification ([20–24]). A technology has been proposed by CEA and Europlasma [25] for implementation in an EF reactor for biomass gasification. The energy efficiency of this technique is expected to be greater than 70%.

Hydrogen addition has been proposed by only a few authors. Bossel et al. [26] argument that hydrogen is more efficiently used when introduced into biofuels. Norbeck et al. [27] propose to add hydrogen in a fluidized bed gasification reactor operated at low temperature (~500 °C) and high pressure in order to produce methane. Agrawal [8], Dietenberger and Anderson [4] and Shinnar and Citro [9] also identified the interest of hydrogen addition in order to increase mass yield in biofuel production. The authors of the present paper also discussed the interest of adding hydrogen [1,5–7].

Different technologies are proposed to add hydrogen. One of them that we propose is to burn hydrogen in an entrained flow reactor because thermodynamic equilibrium calculations at high temperature show that oxygen preferentially reacts with hydrogen. Consequently, it is possible to save more renewable carbon and convert it into CO for fuel synthesis. This technique comes down to moving the external energy input from the gasifier to the hydrogen production device. The energy yield is mainly determined by the hydrogen production yield, but it is about 15% lower due to the energy consumed to heat hydrogen up to 1500 °C.

Natural gas co-combustion can be emphasized as a technique for external energy input, but it supposes that the equivalent amount of fossil carbon (which is produced as CO_2) is captured in the process. This is an advantage in comparison to GtL process, for which the fossil carbon bound in the fuel is released into the atmosphere.

3.3. *Gas cooling*

Three solutions are assessed:

- simple quench down to 800 °C followed by heat recovery down to ~400 °C: it is considered that quench with water induces partial water gas shift,
- chemical quench (syngas reaction with char particles between 1500 °C and ~900 °C) followed by heat recovery in a heat exchanger down to 400 °C,
- heat recovery from 1500 °C down to 800 °C: this technology is not available and requires to develop high temperature gas cleaning.

3.4. *Gas cleaning*

Two solutions are considered:

- “Rectisol cleaning”,
- “water-amine cleaning”.

Part of the energy required for cleaning is recovered from the high temperature syngas.

3.5. *H_2/CO ratio adjustment*

Three alternatives are considered for the adjustment of the H_2/CO ratio:

Table 1
Calculated yields and energy inputs for various process alternatives.

Process	Mass yield % (Diesel/dry biomass)	Energy yield %	Primary energy yield %	Biomass consumption J/J product	Electricity consumption J/J product	Natural gas consumption J/J product
[1] Slurry + Autothermal + Water gas shift (WGS) + no tail gas recycle	18	38	37	2,37	−0,03	0,25
[2] Slurry + Autothermal + H_2 (elec.) + no tail gas recycle	25	39	25	1,69	0,68	0,18
[3] Slurry + Autothermal + H_2 (nat. gas) + no tail gas recycle	25	42	42	1,69	−0,07	0,74
[4] Slurry + Autothermal + WGS + with tail gas recycle	26	47	41	1,64	0,11	0,36
[5] Slurry + Autothermal + H_2 (elec.) + with tail gas recycle	38	48	29	1,13	0,66	0,27
[6] Slurry + Autothermal + H_2 (nat. gas) + with tail gas recycle	38	52	48	1,13	0,07	0,69
[7] Slurry + Autothermal + HT heat exchanger + H_2 (elec.) + with tail gas recycle	45	50	26	0,95	0,85	0,19
[8] Slurry + Autothermal + HT heat exchanger + H_2 (nat. gas) + with tail gas recycle	45	56	49	0,95	0,06	0,76
[9] Slurry + Allothermal (H_2) + HT heat exchanger + H_2 (elec.) + with tail gas recycle	46	47	23	0,93	1,03	0,16
[10] Slurry + Allothermal (nat. gas) + HT heat exchanger + H_2 (elec.) + with tail gas recycle	51	51	28	0,83	0,77	0,35
[11] Slurry + Allothermal (nat. gas) + HT heat exchanger + H_2 (nat. gas) + with tail gas recycle	51	56	49	0,83	0,06	0,87
[12] Slurry + Allothermal (plasma) + HT heat exchanger + H_2 (elec.) + with tail gas recycle	54	52	25	0,79	1,01	0,13
[13] Slurry + Allothermal (plasma) + HT heat exchanger + H_2 (nat. gas) + with tail gas recycle	54	57	37	0,79	0,43	0,53
[14] Torrefied Wood + Autothermal + HT heat exchanger + H_2 (elec.) + with tail gas recycle	50	51	25	0,85	0,98	0,13
[15] Torrefied Wood + Autothermal + HT heat exchanger + H_2 (nat. gas) + with tail gas recycle	50	58	51	0,85	0,06	0,79
[16] Torrefied Wood + Allothermal (nat. gas) + HT heat exchanger + H_2 (elec.) + with tail gas recycle	56	52	26	0,76	0,89	0,26
[17] Torrefied Wood + Allothermal (nat. gas) + HT heat exchanger + H_2 (nat. gas) + with tail gas recycle	56	58	51	0,76	0,06	0,88
[18] Torrefied Wood + Allothermal (plasma) + HT heat exchanger + H_2 (elec.) + with tail gas recycle	59	52	24	0,72	1,08	0,12
[19] Torrefied Wood + Allothermal (plasma) + HT heat exchanger + H_2 (nat. gas) + with tail gas recycle	59	56	35	0,73	0,50	0,54

- a water gas shift reaction: CO conversion into H_2 induces carbon losses,
- input of additional hydrogen from:
  - water electrolysis: the co-produced oxygen is used in the gasification reactor (except for plasma gasification technologies); that has been shown to be interesting in the case of synthetic natural gas production from wood [28];
  - natural gas reforming: it is associated with carbon capture and sequestration if this technology is available.

3.6. *Fuel synthesis*

Different types of fuel can be obtained by synthesis: methanol, DME or Fischer–Tropsch fluids. Only Fischer–Tropsch synthesis will be considered in the present assessment.

3.7. *Use of the tail gas*

Two options have been considered for the tail gas:

- combustion in a gas turbine to produce electricity, which is used in the process,
- recycling and reforming: the tail gas contains CO and H_2 that have not reacted and that can be recycled within the process.

About 100 different processes can be built from all the considered options.

4. Technical comparison of process alternatives

The calculated performances of various process alternatives are compared in Table 1. Some precautions should be taken when analyzing these figures:

- the feasibility of energy addition by plasma is still to be demonstrated,
- high temperature heat exchangers are not industrially available,
- industrial reforming of tail gases should also be assessed,
- more pessimistic hypotheses can lead to lower production yields, by at most −20%; nevertheless, the ranking of the various options would not change in terms of yield.

The interest of introducing these options is mainly to identify their impact on process performances and thus to measure the interest of technical developments. The main conclusions are that:

- ➢ the mass yield varies in a large range: 18%–59%; i.e. about a factor 3 increase,
- ➢ the options that mostly increase the mass yield are in the following order:
  1. replacement of water gas shift by hydrogen addition,
  2. recycling and reforming of the tail gases from the Fischer–Tropsch synthesis,
  3. external energy input in the gasification reactor.

As an illustration, a step-by-step mass balance is given in Table 2 for two options.

The main interest of a high temperature heat exchanger is not so much a higher energy recovery (energy above 800 °C could be used to reform the tail gases) as avoiding partial water gas shift induced by syngas water quench down to 800 °C. Chemical kinetic calculations indicate that syngas chemical quench (reaction with char) induces partial water gas shift too.

A more elaborated preparation, for instance fast pyrolysis (slurry) in comparison to torrefaction (processes 7 and 14, 10 and 16, 12 and 18), leads to a lower mass yield (∼−5% absolute), due to heat and carbon losses during the preparation.

Decentralisation of biomass preparation (not shown in Table 1) is not technically interesting:

- it does not allow to recover the large amount of heat from the fuel synthesis for biomass drying,
- biomass transportation only consumes a small amount of energy,
- investment and operation costs are increased.

Fig. 2 shows CO_2 emissions and fuel production for the most technically interesting options. Electrical consumption is indicated and natural gas consumption is proportional to CO_2 production (no CO_2 capture and sequestration has been considered). As a reference, the same amount of biomass put into a “basic” process (slurry + autothermal + water gas shift + no tail gas recycle) gives

Table 2
Step-by-step mass balance for two options.

Step	Option 1: process no. 1	Option 2: process no. 16
Biomass preparation	Hot air drying + fast pyrolysis (slurry)	Hot air drying + torrefaction
Input	C6H9O4 +610 kJ (200 °C) +270 kJ (500 °C) +70 kJ (el.)	C6H9O4 +610 kJ (200 °C) +0.075 CH4 +65 kJ (el.)
Main output	C5.2 H7 O2.5 + 1.5 H2O	C5.6 H7 O2.8
Gasification	Entrained flow reactor (1500 °C): autothermal	Entrained flow reactor (1500 °C): co-combustion of natural gas
Additional input	+1.8 O2 (100 kJ (el.))	+0.6 CH4 + 2.6 O2 (cf. H2)
Main output	4.6 CO + 3.2 H2 + 1.7 H2O + 0.6 CO2	5.6 CO + 3.4 H2 + 1.2 H2O + 0.6 CO2
Gas cooling	Water quench	Heat exchanger
Additional input	+4.5 H2O	
Main output	3.6 CO + 4.2 H2 + 5.2 H2O + 1.6 CO2	5.3 CO + 3.7 H2 + 0.9 H2O + 0.9 CO2 + 145 kJ (>800 °C)
Gas cleaning	Water-amine	Water-amine
Additional input		
Main output	3.6 CO + 4.2 H2	5.3 CO + 3.7 H2
H_2/CO adjustment	Water gas shift	Hydrogen addition from water electrolysis
Additional input		+7.4 H2 (2975 kJ (el.))
Main output	2.6 CO + 5.2 H2	5.3 CO + 11.1 H2
Fuel synthesis	Fischer–Tropsch synthesis with tail gas combustion	Fischer–Tropsch synthesis with tail gas recycling
Additional input		+470 kJ (800 °C)
Main output	1.8 CH2 +605 kJ (200 °C) +200 kJ (el.).	5.3 CH2 +1105 kJ (200 °C)

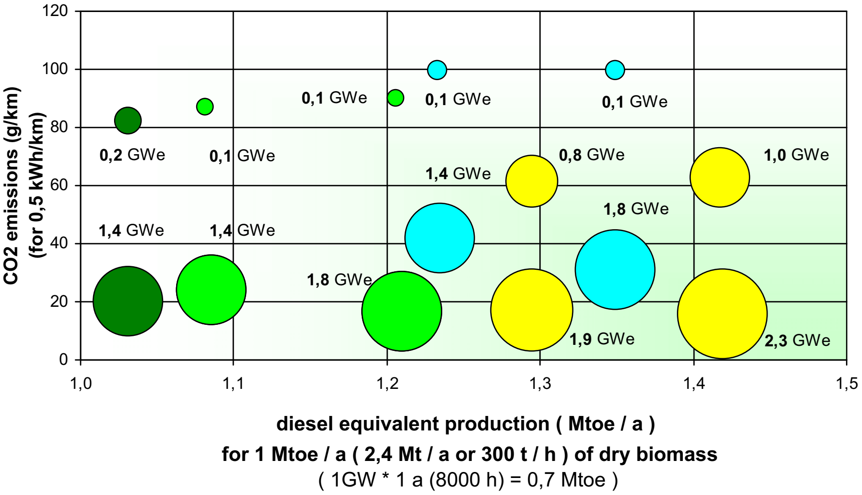

Fig. 2. Technical comparison of different process options: CO_2 emissions (g/km) and diesel fuel production (Mtoe/a) for 2.4 Mt/a dry biomass (300 t/h). The size and figures in GWe correspond to electrical power supply. ● Slow pyrolysis + autothermal gasification + chemical quench + H_2 (elec. (bottom)/nat. gas (top)). ● Slurry (left)/torrefied wood (right) + autothermal gasification + H_2 (elec. (bottom)/nat. gas (top)). ● Slurry (left)/torrefied wood (right) + allothermal gasification (nat. gas) + H_2 (elec. (bottom)/nat. gas (top)). ● Slurry (left)/torrefied wood (right) + allothermal gasification (plasma) + H_2 (elec. (bottom)/nat. gas (top)) (All processes include tail gas recycling. The CO_2 produced in the process is not captured).

~0,45 Mtoe. The processes that are presented involve additional energy input.

Fig. 2 shows that the introduction of natural gas leads to a significant increase of CO_2 production; thus, CO_2 should be captured and sequestrated in that case. Table 1 and Fig. 2 also show that there is a large variety of combinations of options that can lead to a significant increase of the fuel mass yield, because of the possibility of using, at least, two different energy vectors (electricity and natural gas) for the replacement of water gas shift and for gasification. These resources and associated technologies can thus be preferably implemented depending on local constraints on resources, on prices and on available technologies, especially CO_2 sequestration.

5. Economical aspects: EBtL production cost

Production costs are evaluated on following bases:

- reference costs for inputs:
  - biomass: 20 €/MWh (100 €/t dry biomass),
  - electricity: 45 €/MWh,
  - natural gas: 30 €/MWh;
- investment costs are evaluated for a plant treating 100 t/h of dry biomass: they range from 550 M€ to 1200 M€ depending on process options; this capital is considered to be reimbursed within 25 years and actualization rate is taken at 8%;
- other operating costs are taken into account as a fraction of investment costs: 50%.

Table 3 shows the costs evaluated for the technical options discussed above. The main results are that:

➢ production costs range from ~0.72 €/l to 1.13 €/l while mass yields vary by a factor 3;

➢ investment costs contribution to production costs varies between 20 and 33%;

➢ the input of external energy that is more expensive than biomass is more than compensated by the significant increase of production yield: the production cost is generally lower for allothermal processes than for autothermal processes.

Table 3
Production cost evaluation for the different technical options.

Process	Mass yield % (Diesel/dry biomass)	Production cost €/l diesel
[1] Slurry + Autothermal + water gas shift (WGS) + no tail gas recycle	18	1,04
[2] Slurry + Autothermal + H_2 (elec.) + no tail gas recycle	25	1,13
[3] Slurry + Autothermal + H_2 (nat. gas) + no tail gas recycle	25	0,94
[4] Slurry + Autothermal + WGS + with tail gas recycle	26	0,88
[5] Slurry + Autothermal + H_2 (elec.) + with tail gas recycle	38	0,95
[6] Slurry + Autothermal + H_2 (nat. gas) + with tail gas recycle	38	0,79
[7] Slurry + Autothermal + HT heat exchanger + H_2 (elec.) + with tail gas recycle	45	0,95
[8] Slurry + Autothermal + HT heat exchanger + H_2 (nat. gas) + with tail gas recycle	45	0,76
[9] Slurry + Allothermal (H_2) + HT heat exchanger + H_2 (elec.) + with tail gas recycle	46	1,03
[10] Slurry + Allothermal (nat. gas) + HT heat exchanger + H_2 (elec.) + with tail gas recycle	51	0,93
[11] Slurry + Allothermal (nat gas) + HT heat exchanger + H_2 (nat. gas) + with tail gas recycle	51	0,75
[12] Slurry + Allothermal (plasma) + HT heat exchanger + H_2 (elec.) + with tail gas recycle	54	0,89
[13] Slurry + Allothermal (plasma) + HT heat exchanger + H_2 (nat. gas) + with tail gas recycle	54	0,80
[14] Torrefied Wood + Autothermal + HT heat exchanger + H_2 (elec.) + with tail gas recycle	50	0,95
[15] Torrefied Wood + Autothermal + HT heat exchanger + H_2 (nat. gas) + with tail gas recycle	50	0,73
[16] Torrefied Wood+ Allothermal (nat. gas) + HT heat exchanger + H_2 (elec.) + with tail gas recycle	56	0,93
[17] Torrefied Wood + Allothermal (nat. gas) + HT heat exchanger + H_2 (nat. gas) + with tail gas recycle	56	0,72
[18] Torrefied Wood + Allothermal (plasma) + HT heat exchanger + H_2 (elec.) + with tail gas recycle	59	0,89
[19] Torrefied Wood + Allothermal (plasma) + HT heat exchanger + H_2 (nat. gas) + with tail gas recycle	59	0,80

The sensitivity to the costs of the inputs has also been analysed. Following variations are considered:

- biomass: from 15 to 45 €/MWh (75–225 €/t dry biomass),
- electricity: from 45 to 90 €/MWh,
- natural gas: from 15 to 60 €/MWh.

The minimum production cost that is obtained is then 0.5 €/l diesel. When the maximum input costs are considered, the production costs are approximately doubled in comparison to the costs indicated in Table 3.

6. Conclusions

We conclude that massive biofuel production is basically an energetic issue. As renewable biomass is a limited resource (for France, local resources are quite lower than fossil energy consumption), to replace a significant part of fossil fuels with biofuels emitting no fossil carbon into the atmosphere implies to transfer as much renewable carbon as possible into biofuels. This requires additional energy, which can be achieved through hydrogen, electricity or natural gas (with CO_2 capture and sequestration), provided that no greenhouse gases are emitted and the technological pathways are economically viable.

The EBtL routes discussed here enable increased fuel production from renewable biomass: up to 40% of today French consumption for transportation, from local renewable resources evaluated at 50 Mt/a. This significant improvement in biofuel production is due to:

- the input of external energy that maximizes the transfer of renewable carbon from the biomass into the fuel: thus, EBtL routes can also be seen as an efficient way to store electricity and hydrogen (produced from processes emitting no greenhouse gas) into a liquid fuel, compatible with present motor technologies and fuel storage and distribution [7];
- the use of the entire lignocellulose plants and possibly of organic wastes, that offers a broad spectrum of resources: combined with the maximization of the carbon transfer into the final fuel, it reduces the competition with food crops.

The gasification technology discussed here is based on an entrained flow reactor: it is mature for coal and under industrial development for biomass. Techniques to add energy have unequal maturity: addition of hydrogen from natural gas reforming is mature; water electrolysis is ready for upscaling; combustion of natural gas in the gasification reactor should require only light industrial development, as well as recycling of Fischer–Tropsch synthesis tail gas; plasma technologies with higher efficiency still require R&D work.

The calculated EBtL production costs, including investments, range from ~0.7 to ~1.1 €/l (diesel), depending on the process options: the increase in mass yield enables significant cost reductions. Furthermore, the input costs can be shared between several resources, making EBtL cost less sensitive to their separate cost evolutions. A flexible process can also be designed to adapt to resource markets. The production cost of optimised EBtL processes can compete with production costs for CtL and GtL, provided that a "fossil carbon tax" is applied.

EBtL routes may be combined with the development of hybrid cars (fuel and electrical motors) to offer a mid term realistic alternative to petroleum with low greenhouse gas emissions.

References

[1] Ballerini D. Les biocarburants. IFP Publications Editions TECHNIP; 2006.
[2] Gül T, Kypreos S, Turton H, Barreto L. An energy-economic scenario analysis of alternative fuels for personal transport using the Global Multi-regional MARKAL model (GMM). Energy 2009;34(10):1423–37.
[3] Henrich E, Dinjus E. Tar-free, high pressure synthesis gas from biomass. Expert Meeting on Pyrolysis and Gasification of Biomass, Strasbourg; 2002.
[4] Dietenberger MA, Anderson M. Vision of the U.S. biofuel future: a case for hydrogen-enriched biomass gasification. Industrial & Engineering Chemistry Research 2007;46(26):8863–74.
[5] Boissonnet G, Bayle J, Seiler JM, Chataing T, Rougé S, Bertrand C, et al. Comparison of several biomass steam gasification routes and technologies to produce hydrogen and synfuels. 1st European Hydrogen Energy Conference, Grenoble; 2003.
[6] Boissonnet G, Seiler JM, Chataing T, Brothier M, Bertrand C. Pyrolysis and gasification of biomass and waste. In: Bridgwater AV, editor. Proceedings of Strasbourg conference; 2002. p. 385–394.
[7] Hohwiller C, Rougé S, Seiler JM, Imbach J, Luciani JF, Criqui P, et al. Electric grid regulation in a renewable energy supply; application to BtL process. 17th European biomass conference & exhibition, Hamburg; 2009.
[8] Agrawal R, Navneet RS, Ribeiro FH, Delgass WN. Sustainable fuel for the transportation sector. Proceedings of the National Academy of Sciences of the United States of America 2007;104(12):4828–33.
[9] Shinnar R, Citro F. A road map to US. Decarbonization. Science 2006;313 (5791):1243–4.
[10] Rotman D. The price of biofuels. Technology Review; January/February 2008:42–51.
[11] Bridgwater AV. Pyrolysis and gasification of biomass and waste. Proceedings of an expert meeting. Strasbourg, France: CPL Press; 2002.
[12] Warnecke R. Comparison of fixed bed and fluidized bed gasifier. Biomass and Bioenergy 2000;18:489–97.
[13] Dautzenberg K, Hanf J. Biofuel chain development in Germany: organisation, opportunities, and challenges. Energy Policy 2008;36:485–9.
[14] Beenackers AACM. Biomass gasification in moving beds, a review of European Technologies. Renewable Energy 1999;16:1180–6.
[15] Stahl K, Neergard M. IGCC power plant for biomass utilisation, Värnamo, Sweden. Biomass and Bioenergy 1998;15(3):205–11.
[16] Chiaramonti D, Bonini M, Fratini E, Tondi G, Gartner K, Bridgwater AV, et al. Development of emulsions from biomass pyrolysis liquid and diesel and their use in engines-part 1: emulsion production. Biomass and Bioenergy 2003;25: 85–99.
[17] Henrich E, Dinjus E, Weirich F. A new concept for biomass gasification at high pressure. 12th European conference on biomass, Amsterdam; 2002.
[18] Boerrigter H, van der Drift A. Large-scale production of Fischer–Tropsch diesel from biomass. Congress on synthetic biofuels – technologies, potentials, prospects, Wolfsburg; 2004.
[19] Minchener AJ. Coal gasification for advanced power generation. Fuel 2005;84: 2222–35.
[20] Les plasmas dans l'industrie. Collection Electra; 1991.
[21] Camacho SL. US patents 4559439; 4549065; 4625092; 4587397; 4694464; 5362939; 97/08494.
[22] Robert. US patent 6,173,002 B1.
[23] Zhao Zengli, Huang Haitao, Wu Changzhi, Li Haibin, Chen Yong. Biomass pyrolysis in an argon/hydrogen plasma reactor. Engineering in Life Sciences 2001;1(5).
[24] Van Oost G, Leys C, Joos M, van Heesh B, Hrabovsky M, Sunka P. Plasma based total treatment of waste and low-grade fuels. Czechoslovak Journal of Physics 2002;52:D784–93.
[25] French patents DD 2685 YL, EN 04 51021 and patent WO/2007/042559. Device for gasifying biomass and organic wastes at a high temperature and with an external power supply for generating a high quality synthesis gas.
[26] Bossel U, Eliasson B, Taylor G. The future of the hydrogen economy: bright or bleak?, www.efcf.com/reports/E08.pdf; 2005.
[27] Norbeck JN, Johnson K. Evaluation of a process to convert biomass to methanol fuel NRMRL-RTP-202.
[28] Gassner M, Maréchal F. Thermo-economic optimisation of the integration of electrolysis in synthetic natural gas production from wood. Energy 2008;33 (2):189–98.